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Abstract

We present measurements and modeling results of the electrical conductor "strips" deposited on microchannel plate (MCP) x-ray detectors. Short pulse mode response of the MCP is extremely sensitive with the output intensity related to the applied voltage by up to $V^{15\text{-}25}$. Thus any voltage drop as the pulse travels along the strip due to conductor losses, surface roughness, etc. leads to significant changes in recorded signal intensity. This is commonly referred to as gain droop with typical variations of >3x over a 7mm x 34mm strip (3% change in voltage ~2x change in gain). In an effort to minimize this gain droop we investigate electrode material choice, material thickness, and effects of annealing on the DC ohmic loss of the strip.

Additionally any reflected energy due to impedance mismatches at the output of the MCP, or crosstalk between strips, may superimpose on the incident voltage pulse, again causing gain variations. Impedance matching measurement tools and techniques for ~10ohm MCP's will be discussed.

Introduction

Gated X-Ray Detector (GXD) cameras are primary target diagnostic tools on the National Ignition Facility (NIF). They are used to capture a series of high speed images (~100ps exposure per image) of an imploding target creating a "movie" of the event.

In order to capture as many images as possible the cameras have multiple exposure windows, or strips, which only capture images when a voltage is applied, thus "opening the gate". Figure 1 depicts a 4 strip version in which the top strip is active first followed in succession by the ones below. The order of activation of each of the strips and relative timing is configurable.

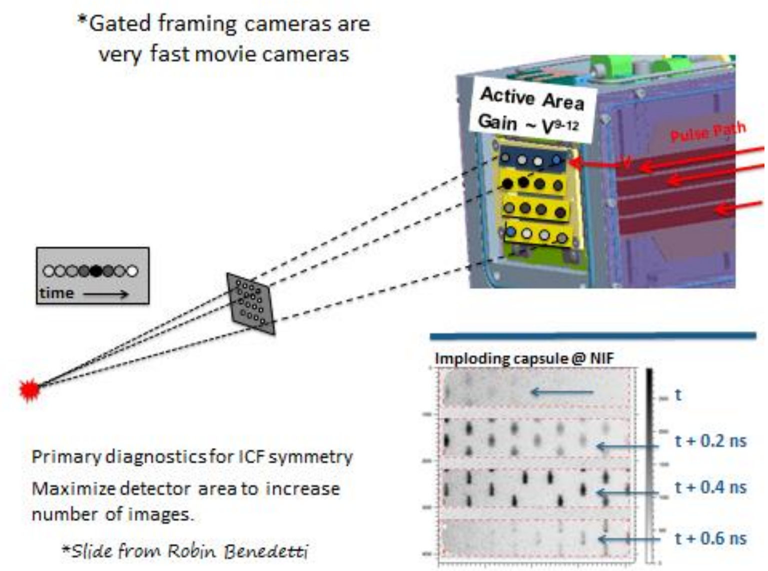


Figure 1: Gated X-Ray "Movie" Camera

Each strip is actually an electrode microstrip deposited onto a high gain microchannel plate (MCP). The gain through the MCP is approximately $V^{15\text{-}25}$ or more. With this much gain per volt, a 50V voltage drop is approximately 3x change in gain. Preferably the gain would be uniform along the strip to simplify analysis and more importantly to maintain sufficient signal to noise ratio of the image.

To keep the exposure time short, a ~1kV, ~200ps pulse is launched onto the microstrip electrode from one end, as it propagates the X-rays coincident with this electrical pulse produce electrons which strike the phosphor, emitting light. Finally, either film or a CCD camera captures the light from the phosphor creating the desired series of pin-hole images. (Figure 2).

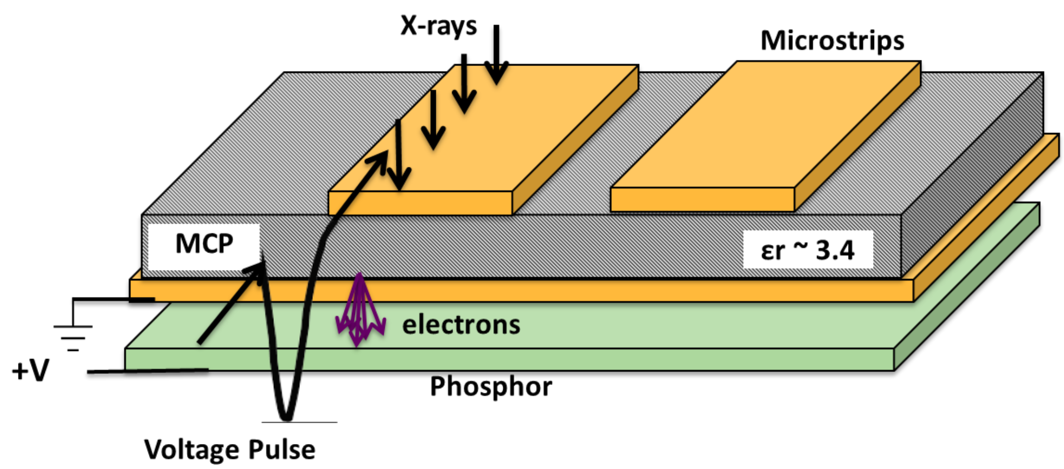


Figure 2: Voltage Pulse Launched onto Strip 1 to Open Gate to X-Rays

Due to various losses along the microstrip the pulse loses amplitude, and thus MCP gain, as it propagates from one end of the strip to the other. (Figure 3).

There are other concerns, such as reflections off the far end folding back on the still forward propagating pulse and cross talk between strips some of which will be addressed following the discussion regarding the voltage drop due to ohmic loss of the microstrip materials and structure.

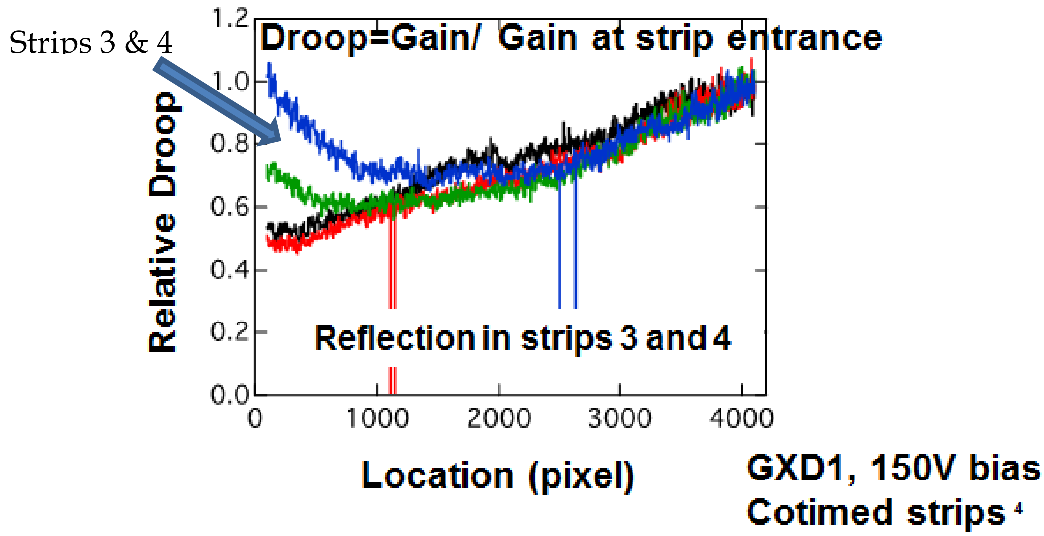


Figure 3: Relative gain across the MCP (pulse travels from right to left)

Discussion

There is a desire to reduce the signal gain variations as a function of position (gain droop) for microchannel plate Gated X-ray Detectors (GXD). One aspect to be understood and properly addressed is the stackup of the microstrip electrodes on the MCP which carry the gating high voltage pulse. The initial portion of this investigation deals with material interaction (copper and gold diffusion), mitigation, and benefits of annealing the electron beam deposited conductors.

Under normal circumstances the ohmic losses are not the dominate source of voltage loss leading to gain droop. Future work is required to fully model the microstrips and understand which factor is dominate however the structure of the MCP especially “surface roughness” due to the MCP pores is strongly suspected.

Traditionally a thin layer of gold has been deposited onto the copper electrode to avoid oxidation and ensure reliable electrical contact with the support circuitry. Scrutiny of this material stack up raised concerns of the gold on copper structure due to diffusion[i]. Further, the alloy formed has a much higher resistivity than either of the component metals[ii], and once the copper completely penetrates the gold it accumulates on the surface where it will oxidize and form a highly resistive layer interfering with electrical contacts[iii].

As the primary conductor of the MCP microstrip is electron beam deposited copper, annealing to affect grain boundaries should lead to higher conductivity and less loss. It was recognized that raising the temperature of a layered structure of copper and gold would accelerate the diffusion process increasing the net voltage drop and corresponding gain droop. We investigate creating a boundary layer between the copper and atmosphere which is stable (no diffusion) and provides low contact resistance.

An analytic model was constructed (Figure 4) accounting for geometry and the various material conductivities followed by measurements of deposited microstrips on bare fused silica glass plates acting as surrogates for MCPs. Calculated vs measured total conductivity was used as a proxy for various loss characteristics including, grain boundary variations due to e-beam deposition, annealing effects, material diffusion, and electrical contact efficiency.

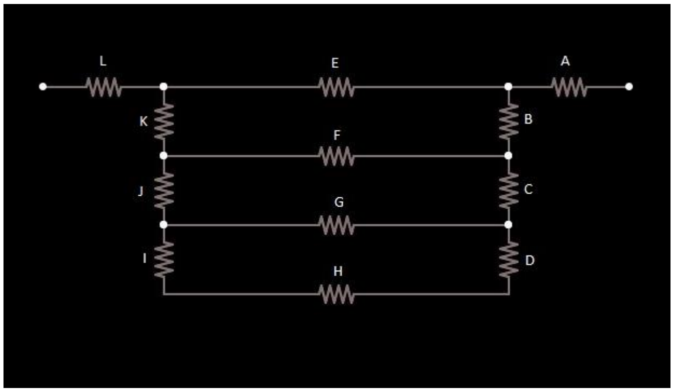


Figure 4: Electrical Model of 3D Multilayer Microstrip

A progression of electrode material stack ups and annealing times at 300degC were evaluated with differences from expectations based on the bulk material resistivity and measured resistances ranging from >40% for Cr-Cu (indicating oxidation interfering with the electrical contact) to <10% for Cr-Cu-Oxide-Anneal.

Comparison of freshly deposited microstrips of our standard protocol (Nd-Cu-Au) and the protocol with least variation from calculation (Cr-Cu-Oxide-Anneal) results in an 11% reduction in ohmic losses, (190mOhm vs 211mOhm) with a 4.5% reduction in the resulting gain droop.

These tests indicate the majority of the observed gain droop for freshly deposited microstrips is not from the composition or protocol of the microstrips. However, over time the absolute gain and gain droop could be significantly affected due to copper/gold diffusion leading to increased contact resistance as well as increased resistivity of the resultant alloy. (Figure 5)

Primary Conductors	Expected mOhm	Calculation vs Meas. difference	Actual mOhm	IR Vdrop	Vpulse	Realized Gain $y = 6E\text{-}42x^{15.947}$	Gain Droop Factor
Ideal	0	NA	0	0	1000	4160555	
6000Cu (annealed)	174	9.00%	190	19	981	3065751	**1.36**
5000Cu+1000Au (Initial)	182	16.00%	211	21	979	2962776	**1.40**
4000Cu+2000Au-Cu (50/50 Alloy)	242	NA	242	24	976	2815063	**1.48**
6000Cu-Au (80/20 Alloy)	543	NA	543	54	946	1708011	**2.44**

Figure 5: Microstrip protocols and resulting Gain Droop Factors

Other considerations:

Full 3d electromagnetic modeling (EM) predicts the inner strips should have higher gain than the outer strips due to the inhomogeneity of the microstrip structure near the edges of the MCP. Good agreement was obtained for hGXD 6 between observed gain differences and those predicted from the EM model. This suggests the geometry of the outer strips should be adjusted to match the impedance of the inner strips.

Going forward:

1) The proposed new protocol (Cr-Cu-Oxide-Anneal) is realizable at our facility, has a similar resistivity (~3% lower) than our current protocol for a given geometry, and exhibits good electrical contact properties. We are in process of testing its long term stability.
2) Literature research to date indicates copper gold diffusion could be a concern for our systems due to copper accumulating on and just below the gold surface. Any copper which fully reaches atmosphere can oxidize increasing contact resistance while that below the surface will be within the skin depth of the electrical gate pulses increasing strip resistance.
   a. We should form a better understanding of the time scales involved
   b. We should investigate past calibration data for signs of gain changes
3) The use of Cr-Cu-NiP-Au[iv] has been put forward by R. K. Sharma in "Progress in Electromagnetics Research Letters, Vol 29, 175-184, 2012. These materials warrant further investigation if they are compatible with our coating vendor's equipment.
4) The >300% gain droop observed on newly plated MCPs is not due to ohmic losses of the microstrip, unless complete diffusion of the Cu-Au has already occurred.
   a. Re-measurement of the reference plate (Nb-Cu-Au) which has been stored for ~1yr in a dry nitrogen cabinet indicates no change in resistivity.
   b. Develop EM model of the porous substrate and "rough" surface interface between the substrate and the electrodes
5) Consider tapering the microstrip to change the impedance as the pulse propagates, counteracting accumulated losses. With a gain of $6E\text{-}42x^{15.947}$ approximately 7% voltage decrease corresponds to 3x gain droop. Decreasing the trace width from ~7mm to 6mm

(+/- 0.5mm) will maintain the initial voltage throughout the strip and eliminate voltage droop with minimal impact on useful data collection area.

   a. Reflections due to the gradual impedance change of the strip are expected to be of low amplitude and low frequency content as observed on the Klopfenstein taper launch boards. (See J. Lugten Et. Al. SPIE 2015, San Diego) (Figure 6)

6) Adjust the impedance of the outer MCP strips to account for the realized gain difference due to the edge effect on the electromagnetic field and resulting voltage profile.

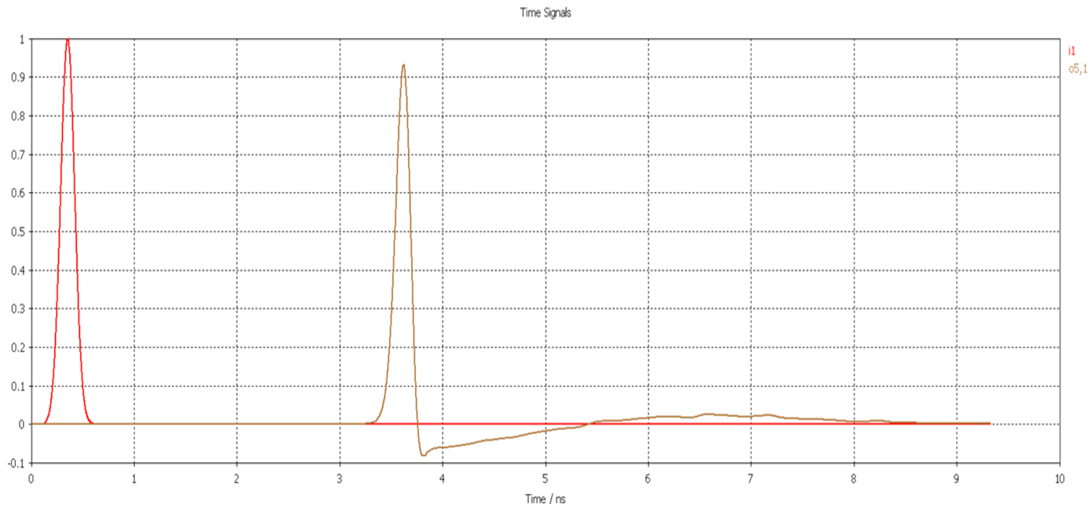
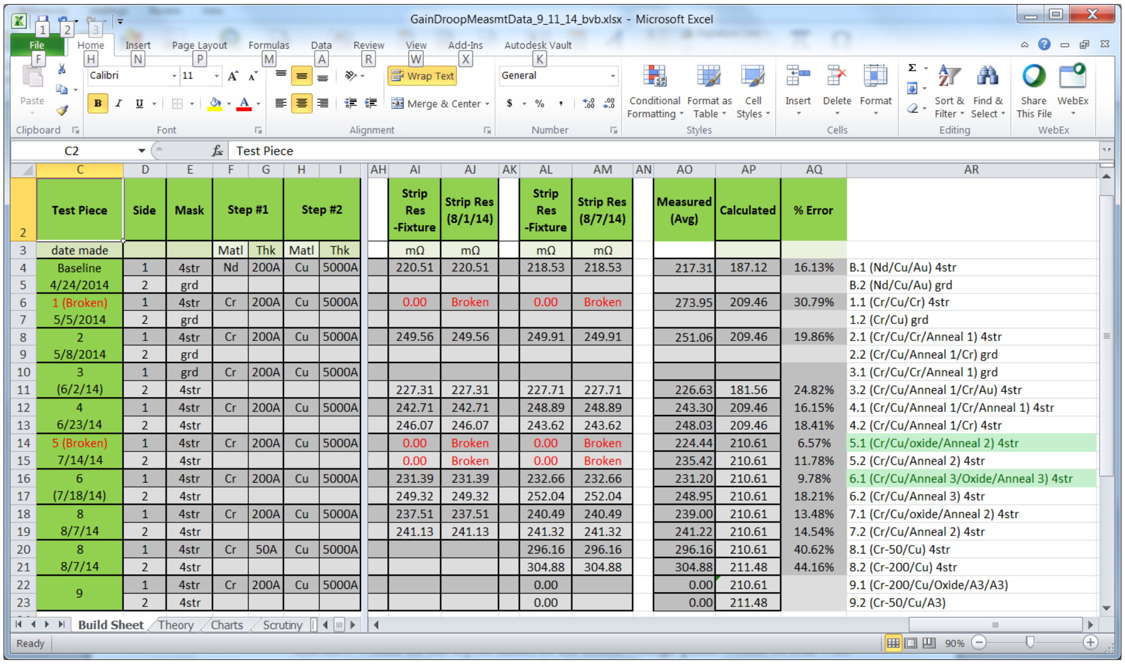


Figure 6: Input and Output Pulses of a 50 to 10ohm Klopfenstein taper

Material Stackup and deposition protocol

LLNL material experts from the chemistry department and from the in house plating shop were consulted regarding adhesion layers and material interaction. Their expertise allowed development of a series of test samples and protocols for our experiments. The progression allowed exploration of ohmic loss minimization which also would be supported by the exterior vendor responsible for “mass production” of the MCPs used by the target diagnostics community.



	C	D	E	F	G	H	I	AI	AJ	AL	AM	AO	AP	AQ	AR
2	Test Piece	Side	Mask	Step #1		Step #2		Strip Res -Fixture	Strip Res (8/1/14)	Strip Res -Fixture	Strip Res (8/7/14)	Measured (Avg)	Calculated	% Error	
3	date made			Matl	Thk	Matl	Thk	mΩ	mΩ	mΩ	mΩ				
4	Baseline	1	4str	Nd	200A	Cu	5000A	220.51	220.51	218.53	218.53	217.31	187.12	16.13%	B.1 (Nd/Cu/Au) 4str
5	4/24/2014	2	grd												B.2 (Nd/Cu/Au) grd
6	1 (Broken)	1	4str	Cr	200A	Cu	5000A	0.00	Broken	0.00	Broken	273.95	209.46	30.79%	1.1 (Cr/Cu/Cr) 4str
7	5/5/2014	2	grd												1.2 (Cr/Cu) grd
8	2	1	4str	Cr	200A	Cu	5000A	249.56	249.56	249.91	249.91	251.06	209.46	19.86%	2.1 (Cr/Cu/Cr/Anneal 1) 4str
9	5/8/2014	2	grd												2.2 (Cr/Cu/Anneal 1/Cr) grd
10	3	1	grd	Cr	200A	Cu	5000A								3.1 (Cr/Cu/Cr/Anneal 1) grd
11	(6/2/14)	2	4str					227.31	227.31	227.71	227.71	226.63	181.56	24.82%	3.2 (Cr/Cu/Anneal 1/Cr/Au) 4str
12	4	1	4str	Cr	200A	Cu	5000A	242.71	242.71	248.89	248.89	243.30	209.46	16.15%	4.1 (Cr/Cu/Anneal 1/Cr/Anneal 1) 4str
13	6/23/14	2	4str					246.07	246.07	243.62	243.62	248.03	209.46	18.41%	4.2 (Cr/Cu/Anneal 1/Cr) 4str
14	5 (Broken)	1	4str	Cr	200A	Cu	5000A	0.00	Broken	0.00	Broken	224.44	210.61	6.57%	5.1 (Cr/Cu/oxide/Anneal 2) 4str
15	7/14/14	2	4str					0.00	Broken	0.00	Broken	235.42	210.61	11.78%	5.2 (Cr/Cu/Anneal 2) 4str
16	6	1	4str	Cr	200A	Cu	5000A	231.39	231.39	232.66	232.66	231.20	210.61	9.78%	6.1 (Cr/Cu/Anneal 3/Oxide/Anneal 3) 4str
17	(7/18/14)	2	4str					249.32	249.32	252.04	252.04	248.95	210.61	18.21%	6.2 (Cr/Cu/Anneal 3) 4str
18	8	1	4str	Cr	200A	Cu	5000A	237.51	237.51	240.49	240.49	239.00	210.61	13.48%	7.1 (Cr/Cu/oxide/Anneal 2) 4str
19	8/7/14	2	4str					241.13	241.13	241.32	241.32	241.22	210.61	14.54%	7.2 (Cr/Cu/Anneal 2) 4str
20	8	1	4str	Cr	50A	Cu	5000A			296.16	296.16	296.16	210.61	40.62%	8.1 (Cr-50/Cu) 4str
21	8/7/14	2	4str							304.88	304.88	304.88	211.48	44.16%	8.2 (Cr-200/Cu) 4str
22	9	1	4str	Cr	200A	Cu	5000A			0.00		0.00	210.61		9.1 (Cr-200/Cu/Oxide/A3/A3)
23		2	4str							0.00		0.00	211.48		9.2 (Cr-50/Cu/A3)

Figure 7: Matrix of Microstrip Electrode Stackup and Process Steps

Test Method and Setup

The strips to be measured are multi-layered metallic structures which function as low impedance microstrips at Ghz frequencies. In practice contact patches of equivalent dimensions are employed on both ends in an effort to maintain a consistent impedance profile for ~100ps pulse propagation.

Initially a four point sheet resistance probe was employed to measure the properties of the electrode strips; however measurement results were inconsistent with calculations for multilayered structures. We suspected the 4 point sheet resistance probe was not able to penetrate the top layer sufficiently to realize the current carrying capabilities of the entire structure.

The next configuration relied upon large contact patches of indium solder (Figure 8) allowing sufficient contact area for DC current to flow down into the 3D structure and flow within all the layers much as the actual voltage pulse would. A four wire ohm meter provided the microstrip ohmic readings.

> It should be noted that for a 100ps pulse the skin depth is ~1um
> Our entire microstrip stack up height is ~0.6um
> DC ohmic values are consistent with the purely ohmic values experienced by the 100ps pulse as the entire structure is involved in the pulse propagation.

The final test fixture relied upon this concept in a format allowing more rapid and repeatable measurements. (Figure 9)

Figure 8: Four Strip MCP surrogate with large ohmic contact patches

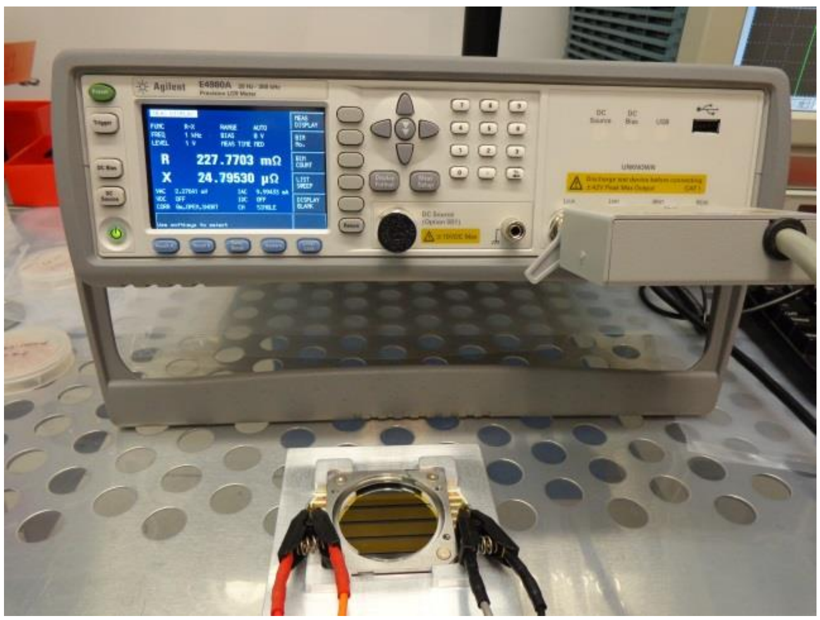


Figure 9: Test Fixture for measuring strip resistance

Tapered Microstrips

The impedance of the microstrips could be tailored to compensate for the observed gain droop. From data obtained from hGXD 6 characterization the gain of the MCP has been determined; $\mathbf{y = 3E\text{-}39x^{15.124}}$ (Figure 10).

To counter the effect of a 3x gain droop a ~10ohm microstrip would taper in width by +/-7.5% from ~7mm at the launch end to ~6mm at the output.

Reflections from the change in impedance should be of the same form as those from the Klopfenstein taper (Figure 6) and not affect the main pulse significantly nor increase cross coupling.

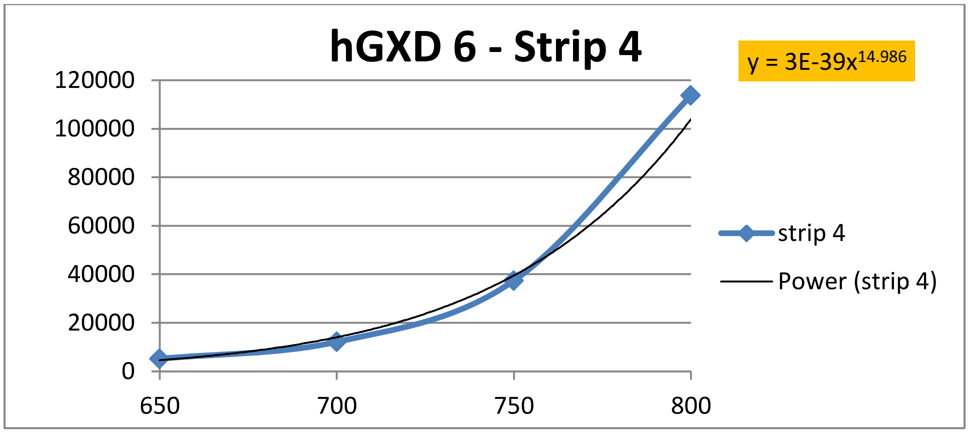


Figure 10: hGXD 6 Gain Profile

Inner strip vs outer strip relative gain

Ideally the gain would be consistent along the entire length of each strip. In addition each strip would have the same gain. Characterization data from hGXD 6 has shown that the outer strips have less gain than the inner strips. (Figure 11).

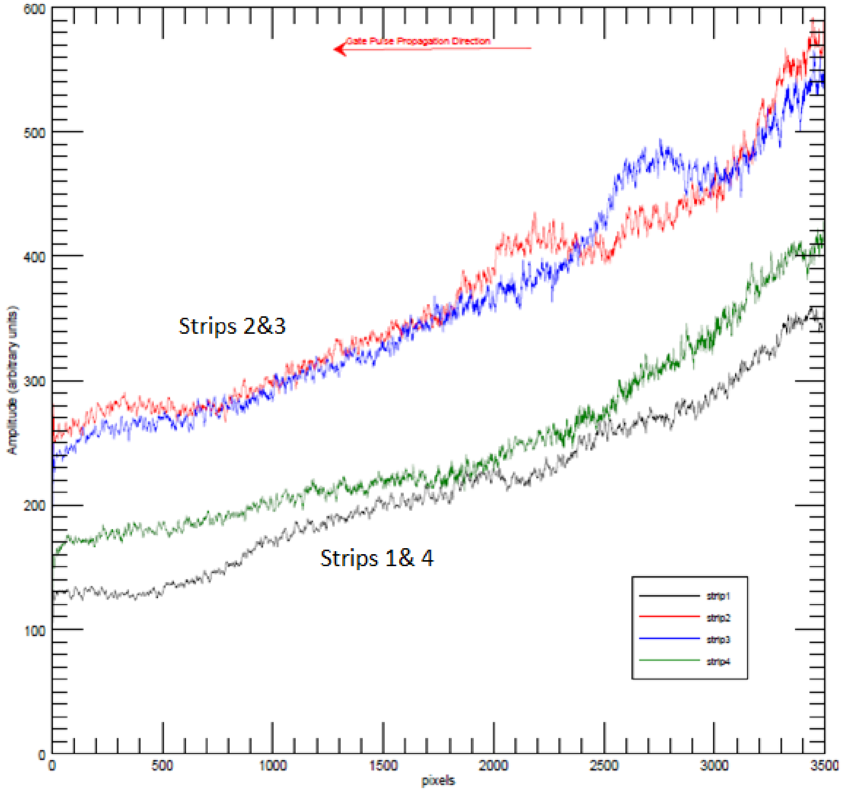


Figure 11: Relative Gain of hGXD 6

Further, 3D electromagnetic modeling reveals the inner and outer strips experience different effective microstrip configurations due to the lack of substrate and ground plane off of the MCP. (Figure 12)

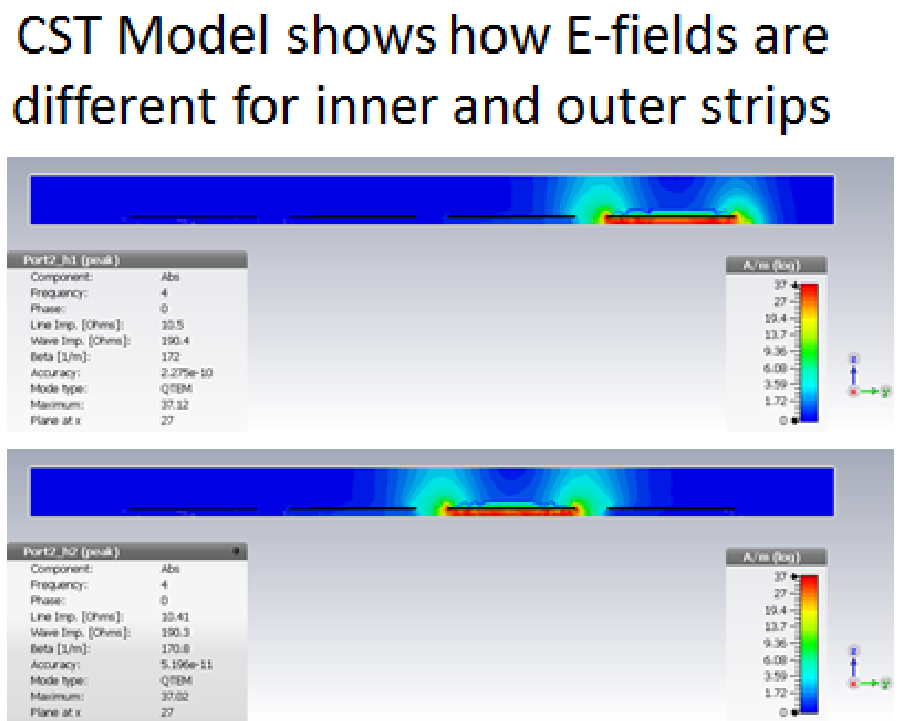


Figure 12: EM fields of inner and outer microstrips

The difference in EM fields leads to different pulse voltages at the end of the microstrips. (Figure 13)

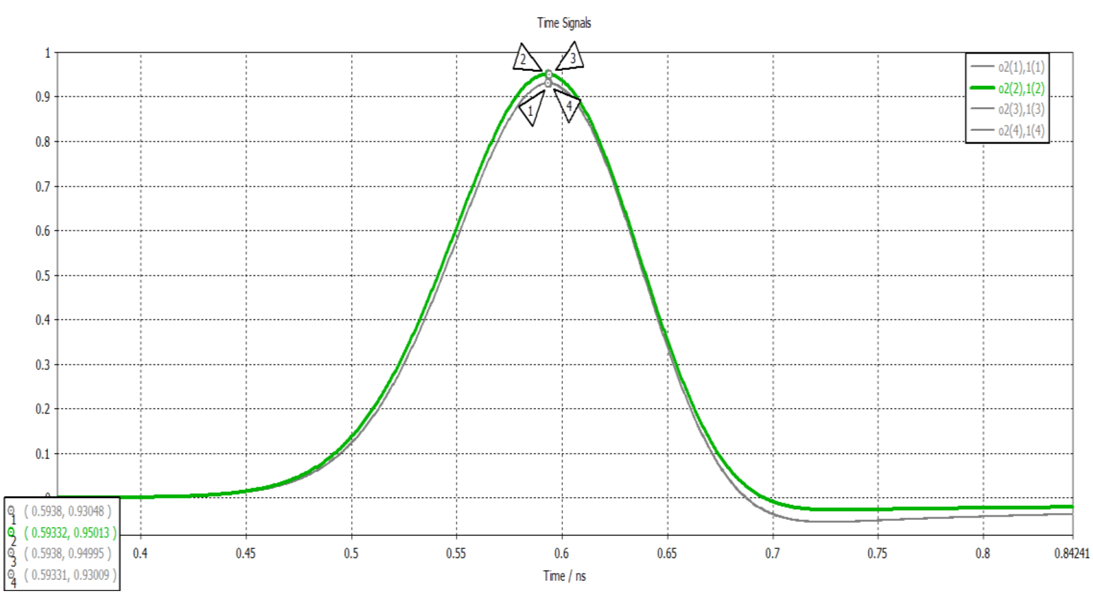


Figure 13: Inner and outer microstrip pulse amplitudes at far end of the microstrip

Finally the difference in pulse amplitudes predicted from the EM model can be cross checked by scaling the observed gain curve of the outer strip and compare the resulting gain with that observed for the inner strips. (Figure 14)

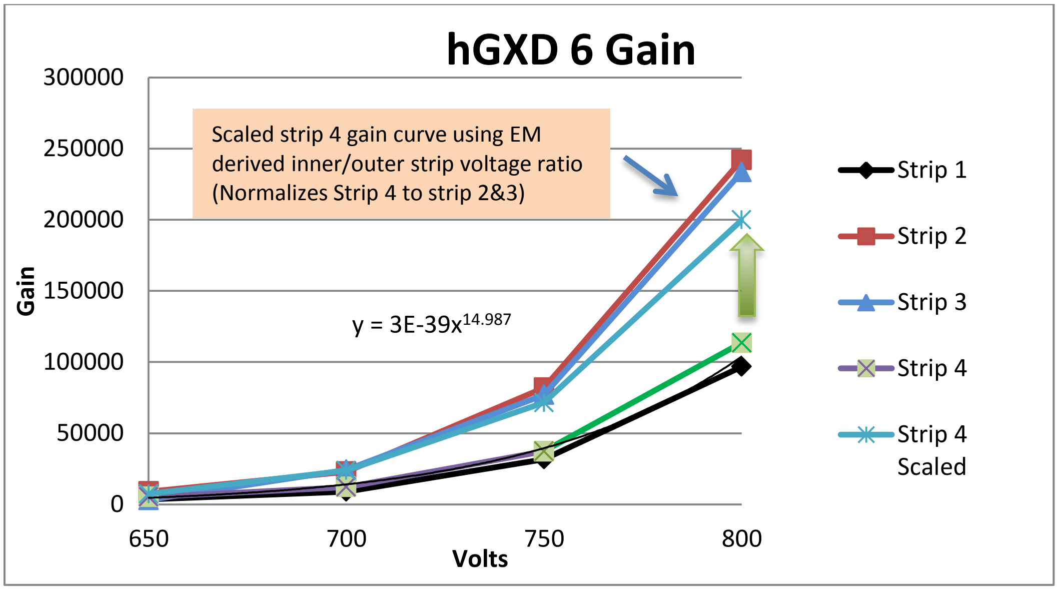


Figure 14: hGXD 6 gain curves including "corrected" strip 4

Microstrip tuning for feature compensation

Components ranging from DC blocking capacitors to clamping mechanisms, bias insertion resistors etc. are required to be in the microstrip voltage path. Through careful planning most of these can be placed such that the effect of any impedance discontinuities can be temporally located so as not to interfere with the primary pulse shape or amplitude.

However, it may be that some discontinuities of concern remain, such as perturbations from the MCP clamping structure. In such cases it may be possible to minimize their effect using counteracting microstrip structures as depicted below. (Figure 15)

Figure 15: Use of microstrip tuning to reduce parasitic "features"

Conclusion

Gain droop in microchannel plate gated X-ray detector systems has many contributing factors including ohmic losses, substrate losses, "surface roughness" losses due to the MCP structure, and general microstrip configuration losses among others.

Ohmic losses don't normally significantly affect gain droop but have the potential to if diffusion of copper and gold is allowed to occur. A Ghz compatible microstrip barrier is required between the copper and either a top gold layer or the atmosphere.

We propose a new protocol (Cr-Cu-Oxide-Anneal) in which chrome forms an adhesion layer between the MCP and the copper which is then exposed to atmosphere before annealing. The final structure allows for good electrical connections, low ohmic losses and would avoid diffusion issues. Long term or accelerated aging is required to ensure surface oxidation does not occur affecting contact resistance.

EM modeling has also been shown to be a good predictor of inner to outer strip gain variation indicating strip impedances (i.e. widths) should be tailored for equal gain on all 4 strips.

It has also been calculated that a +/- 0.5mm (+/-7.5%) taper would be sufficient to overcome the inherent losses of the MCP allowing for a flat gain profile along the length of the strips.

Future work:

1) Verify gold is not required for off line low energy x-ray calibration
2) Data mine past calibration files for indication of changes in observed gain
3) Continue monitoring of aging effects of various material stack ups
4) Investigate compatibility of Cr-Cu-NiP-Au with our processes
5) Construct electromagnets model of complete MCP
   a. Use EM “screen” models for initial investigation
   b. Construct MCP “unit cell” and build up larger structure
6) Investigate use of +/-5% taper to overcome gain droop
7) Adjust relative widths on inner vs outer strips to counter effective microstrip profile
8) Investigate alternatives to present clamp structure
   a. EM model of impedance profile
      i. Consider adding features to counter act effects of impedance perturbations
   b. Avoid trapped air in pores from clamp structure (potential HV weak spots)
      i. Replace clamp with low temperature solder?
9) Compensate launch and receiver pcb traces where pcb is bent?

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[i] D. Butrymowicz Et Al.; Diffusion in Copper and Copper Alloys Part II. Copper-Silver and Copper-Gold Systems

[ii] C. Y. Ho Et. Al; Electrical Resistivity of Ten Selected Binary Alloy Systems

[iii] S. Pucic; NIST, Boulder Co; Diffusion of copper into gold plating

[iv] R. K. Sharma; A Novel Four Layer Metallization For Microwave Integrated Circuits

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